NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE

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EFFECT OF PRESSURE RECOVERY ON THE PERFORMANCE OF A JET-PROPELLED AIRPLANE

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SUMMARY

A study has been made to evaluate the effect of pressure recovery on the performance of a typical jet engine and of a typical jet-propelled fighter airplane. It was found that the pressure-recovery efficiency of an airplane air-induction system is best represented by ram-recovery ratio, which is the ratio of the impact pressure recovered to the impact pressure available. The effect of ram-recovery ratio on the net thrust and on the specific fuel consumption of a turbojet engine was calculated for various speeds and for altitudes from sea level to 40,000 feet. The resulting changes in maximum speed, range, and climbing performance of the airplane are indicated.

For an airplane flying 650 miles per hour at sea level, an increase in ram-recovery ratio from 0.70 to 0.90 will result in an 18.9-percent increase in net thrust and a 9.5-percent decrease in specific fuel consumption. From these and other similar effects indicated in the performance analysis, it would appear that the attainment of high ram recovery should be given major consideration. The analysis shows further that ram recovery will become of greater importance in obtaining optimum performance as airplanes are developed which have higher drag-divergence Mach numbers and which utilize more powerful jet engines.

INTRODUCTION

Because of the development of the turbojet engine and increasing airplane speeds, the problem of taking in the air and ducting it to the compressor inlet with a minimum pressure loss has assumed a greater importance. This increased significance is due to the thermodynamic cycle of the jet engine, the power output being a function of the total pressure and temperature of the air at the compressor inlet.

Performance estimates that have been made for airplanes using turbojet engines usually assume a constant pressure-recovery efficiency. While this assumption is reasonable for a particular air-induction system (air intake and internal ducting to the compressor inlet), it does not allow the designer sufficient latitude for determining the effect of pressure-loss variations.

The purpose of this investigation was to evaluate the importance of the pressure-recovery efficiency of the air-intake system, and determine its effect on the performance of a typical jet-propelled airplane. To make the study, a parameter was selected which adequately indicated the efficiency of the air-induction system.

SYMBOLS

The symbols used throughout this report are defined as follows:

c_p specific heat at constant pressure, Btu's per pound per degree Rankine

F thrust, pounds

g gravitational acceleration, feet per second per second

H total pressure, pounds per square foot

M Mach number

N engine rotational speed, revolutions per minute

p static pressure, pounds per square foot

q dynamic pressure, pounds per square foot

T total temperature, degrees Rankine

t static temperature, degrees Rankine

V velocity, feet per second

W_a air flow to turbojet engine, pounds per second

γ ratio of specific heat at constant pressure to specific heat at constant volume

$$(1 + \eta) = \left(1 + \frac{M^2}{4} + \frac{M^4}{40} + \frac{M^6}{1600} - \frac{M^8}{80,000} \cdot \cdot \cdot\right)$$

Subscripts

o free-stream conditions

1 conditions at the compressor inlet

DISCUSSION

Efficiency Parameters for Air-Induction Systems

Air entering the air-induction system of a turbojet airplane usually undergoes diffusion which increases the pressure and temperature while substantially reducing the air velocity relative to the airplane. Many parameters have been used to indicate the efficiency of this compression process. Of these numerous parameters, ram-recovery ratio was selected as most suitable for presenting the pressure losses of an air-induction system. The reasons for this choice will be discussed; and other commonly used parameters will be reviewed and compared with ram-recovery ratio.

It was considered that an efficiency parameter, to adequately indicate the pressure losses of an air-induction system, should have the following characteristics:

1. Be readily measurable

2. Have a maximum value of unity (or 100 percent) to indicate the maximum possible theoretical efficiency, or the case of zero pressure loss

3. Remain essentially constant for the subsonic-speed range (provided there are no energy losses due either to shock formation or separation resulting from changes in Reynolds number)

Ram-recovery ratio.- A parameter, used by many to indicate the performance of an air-induction system, especially at Mach numbers up to 1.0, is the ratio of the impact (or ram) pressure recovered to the impact pressure available $\left(\frac{H_1 - p_o}{H_o - p_o}\right)$. The maximum value of this parameter cannot be greater than 1.0, and it is readily measurable. To determine the constancy of ram-recovery ratio with Mach number,

experimental data have been used. These data were obtained by Naumann (reference 1) from tests of diffusers at high subsonic speeds. It may be seen in figure 1 that ram-recovery ratio, computed from these test results, varied negligibly up to a Mach number of 0.90. A similar negligible change was found for a Mach number range from 0.30 to 0.875 in tests of an NACA submerged-inlet installation. Ram-recovery ratio, therefore, meets completely the criteria previously listed.

Dynamic pressure-recovery ratio.- The quantity $\frac{H_1 - p_o}{q_o}$ or $1 - \frac{\Delta H}{q_o}$ is sometimes used in presenting pressure losses, especially at low subsonic Mach numbers. It has, however, several disadvantages. The ratio $\frac{H_1 - p_o}{q_o}$ can have values either less or greater than 1.0, the latter usually being the case for high Mach numbers and low pressure losses. Figure 1 shows that, for a given air-induction system, this representation of the experimental pressure losses does not remain constant with increasing M_o. Dynamic pressure-recovery ratio is related to ram-recovery ratio by the compressibility factor $(1 + \eta)$.

Total-pressure ratio.- One parameter which has direct application in turbojet-performance calculations is the ratio of the total pressure at the compressor inlet to the free-stream total pressure, H_1/H_o. It is related to ram-recovery ratio by the following expression:

$$\frac{H_1}{H_o} = \frac{\frac{H_1 - p_o}{H_o - p_o}\left[\left(1 + \frac{\gamma - 1}{2} M_o^2\right)^{\frac{\gamma}{\gamma-1}} - 1\right] + 1}{\left(1 + \frac{\gamma - 1}{2} M_o^2\right)^{\frac{\gamma}{\gamma-1}}}$$

which is derived in Appendix A. The computed variation of this relationship is shown in figure 2. Total-pressure ratio has the disadvantage in that experimental losses of a given air-induction system presented in this form vary with Mach number considerably more than if they were given as ram-recovery ratios. (See fig. 1.)

Pressure ratio.- The ratio of total pressure at the compressor inlet to the ambient static pressure H_1/p_o is, in most turbojet-engine-performance manuals, directly applicable for computation of net thrust, air flow, and specific fuel consumption. Its relationship

to ram-recovery ratio is presented in figure 3. The experimental air-induction-system pressure losses given in terms of H_1/p_o do not remain constant with Mach number, and are not shown on figure 1 because of their relatively large values in comparison with the other parameters. For present day air-induction systems this ratio would have a value greater than 1.0, which for denoting an efficiency is not desirable.

Energy ratio.- Another parameter that is sometimes used is the energy ratio. It is defined as the amount of kinetic energy recovered by the air-induction system divided by the kinetic energy available in the air stream relative to the airplane. This ratio is derived in Appendix B and may be written as

$$\text{Energy ratio} = 1 - \frac{2}{(\gamma-1)\ M_o^2}\left[\left(\frac{H_o}{H_1}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]$$

The variation of this energy ratio with Mach number for constant values of ram-recovery ratio is shown in figure 4. The energy ratio has been known under a variety of different names and forms. Some authors refer to it as an energy efficiency, while others call it a diffuser efficiency. It is equivalent to the adiabatic compression efficiency commonly used to denote supercharger and blower performance. (See reference 2.)

The principal disadvantage of using energy ratio to present air-induction-system losses is that it involves relatively complicated computation. Figure 1 shows that experimental losses given in this manner have a slightly greater variation with Mach number than does ram-recovery ratio.

From the preceding résumé of the parameters used to indicate the efficiency with which air is ducted from outside the airplane to some station inside (such as the compressor inlet), it would appear that ram-recovery ratio is the only parameter that satisfies all the criteria previously mentioned.

Effect of Ram-Recovery Ratio on the Performance of a Turbojet Engine

The effect of ram-recovery ratio on turbojet-engine performance was calculated for an engine representative of those in use today. This propulsion engine had a thrust of 4000 pounds, an air consumption of 73.0 pounds per second, and a specific fuel consumption of 1.08 pounds per hour per pound of thrust, at the nominal static rating (7700 rpm).

From the concepts of flow similarity, inertia forces, elastic forces, and thermal expansion of the working fluid in the jet-propulsion

engine, certain basic dimensionless parameters have been derived in reference 3. By using constants of proportionality, these dimensionless parameters are changed to "corrected parameters." The "corrected" parameters have been used by engine manufacturers to represent the gross thrust, air-flow rate, and fuel-flow rate as functions of engine speed. From the total temperatures and pressures at the compressor inlet, actual values of gross thrust, air flow, and fuel flow may be computed for any specific condition. As mentioned in reference 3, actual ground tests at various simulated altitudes and flight Mach numbers have substantiated the validity of this method.

As adiabatic flow has been assumed in this analysis, the rise in pressure occurring in the air-induction system will depend only on the Mach number and on the efficiency with which the flow process takes place. The total temperature ratio between the diffused and the ambient air will depend solely on the airplane Mach number. Calculations of the performance of a typical jet engine were made for various altitudes and airspeeds by determining for these conditions the total temperature and, for various ram-recovery ratios, the total pressure at the compressor inlet.

Net thrust at constant speed was computed using the basic performance charts of the representative turbojet engine and the relation

$$F_{net} = \left(F_{gross} - \frac{W_a V_o}{g}\right) - \left[\frac{\Delta F}{\Delta H} - \frac{V_o}{g}\left(\frac{\Delta W_a}{\Delta H}\right)\right] \Delta H$$

On the right-hand side of this equation the quantities in the first parentheses represent the net thrust for a given altitude and airspeed with no pressure losses in the duct system, while the quantities in the brackets represent the change in gross thrust and in ram drag resulting from pressure losses in the duct system. Specific fuel consumption was computed in a manner analagous to that used in computing net thrust.

With the assumption that the jet engine was operating at rated rotational speed, the maximum available net thrust and the specific fuel consumption were computed for true airspeeds up to 650 miles per hour, altitudes from sea level to 40,000 feet, and ram-recovery ratios from 0 to 1.00. (See figs. 5 and 6.) These figures indicate that the effect of ram-recovery ratio on net thrust and specific fuel consumption is small at low subsonic speeds, the effect becoming more pronounced, however, at moderate and high subsonic speeds.

From figure 7 it may be seen that for an increase in ram-recovery

ratio from 0.70 to 0.90, the percentage change in net thrust and specific fuel consumption increases as the airspeed increases. This increase becomes less pronounced as the altitude is increased from sea level to 40,000 feet.

Figure 8 shows that, while the percent loss in net thrust varies almost linearly with ram-recovery ratio, the rate of change of specific fuel consumption with ram recovery is greater at the lower values of this ratio. Therefore, for a given change in ram-recovery ratio, operation of an air-induction system in the high range of ram-recovery ratios would not affect specific fuel consumption as greatly as would operation in the low ram-recovery ratio range. The effect of increasing altitude was to reduce the percentage change in both net thrust and specific fuel consumption.

Further examination of figure 8 indicates that for a constant ram-recovery ratio, a change in airspeed has a large effect on net thrust and specific fuel consumption. This result can be explained by the fact that for a given loss in ram-recovery ratio the percentage loss in total pressure at the compressor inlet is greater at high speeds than at low speeds. For example, a decrease from 0.90 to 0.70 in ram-recovery ratio lowers the total pressure 7.8 percent for 650 miles per hour and only 1.4 percent for 250 miles per hour.

The Effect of Ram-Recovery Ratio on the Performance of a Turbojet Airplane

The airplane chosen for these performance calculations was a typical military fighter. This type of aircraft was selected since it requires maximum performance for all flight conditions. The fighter selected, a single-place single-engine airplane with conventional wing and tail arrangement together with data required for these performance calculations, is shown in figure 9.

The assumed lift and drag characteristics of this airplane are shown in figure 10, and the total drag of the airplane at various altitudes is presented in figure 11. These total drag curves, and the curves for net thrust and specific fuel consumption presented in figures 5 and 6, were used in calculating the performance of the airplane for ram-recovery ratios of 0, 0.20, 0.40, 0.60, 0.80, and 1.00. Where necessary, the variation of gross weight was considered in the performance calculations.

<u>Maximum speed and speed for best climb</u>.— The values of maximum speed were determined from the intersection of the curves representing

thrust available and drag. An example of this procedure is shown in figure 11, the thrust values used being for the condition of

$$\frac{H_1 - p_o}{H_o - p_o} = 1.00.$$

Both the maximum speed and the speed for best climb are shown, in figure 12, to be adversely affected by a decrease in the ram-recovery ratio. The speed for best climb increases with altitude, approaching the maximum level flight speed at the absolute ceiling where they are equivalent. As the ram-recovery ratio decreases, the absolute ceiling becomes lower.

It may be seen from figure 13 that the effect of a change in altitude on percent decrease in maximum speed is less at a high ram-recovery ratio than at a low ram-recovery ratio.

The maximum speed of this typical airplane occurs near sea level. However, the Mach number at which maximum speed is obtained is increased at altitudes above sea level. This is shown in the following table:

Ram-recovery ratio $\frac{H_1 - p_o}{H_o - p_o}$	Mach number at $V_{o_{max}}$		
	Sea level	20,000 feet	40,000 feet
0.20	0.670	0.731	0.709
.60	.725	.768	.751
1.00	.767	.799	.784

By comparing these values with their corresponding level flight drag coefficients (fig. 10), it might be expected that the altitude for maximum speed would vary if the airplane drag characteristics were altered. Figure 14 shows that the maximum speed would occur at a higher altitude if the Mach number for drag divergence, as shown in figure 10, were increased. For this condition, and for ram-recovery ratios above 0.30, the speed of the airplane is greater at 40,000 feet than at sea level. It may also be seen in figure 14 that a given change in ram recovery ratio produces a greater change in maximum speed if the Mach number for drag divergence is increased. The effect of ram-recovery ratio becomes even greater when it is assumed that the airplane having these improved drag characteristics is powered by a 5000-pound-static-thrust jet engine instead of a 4000-pound engine.[1]

[1]It was assumed that the ordinates of figure 5 were multiplied by the ratio of the sea-level static thrusts $\left(\frac{5000}{4000}\right)$.

Consequently, the ram-recovery ratio of the air-induction system will assume a greater importance as airplanes are developed which have higher critical Mach numbers and which are propelled by more powerful jet engines.

Figures 12 and 13 also show that pressure losses in the air-induction system affect the best climbing speed more at sea level than at 40,000 feet. This is a consequence of the variation of available thrust with ram-recovery ratio and altitude (fig. 5) and the variation of total drag with velocity and altitude (fig. 11). The climbing performance is a function of these mutually interdependent factors, which are in turn functions of a given airplane and jet engine.

Rate of climb and time to climb.- The computed rate of climb and time to climb in relation to altitude and to ram-recovery ratio for the typical airplane are shown in figure 15. The rate of climb of the airplane is decreased by a constant reduction in ram-recovery ratio to a greater extent at sea level than at 40,000 feet. However, the percent change is greater at 40,000 feet. (See fig. 16.)

The time to climb to a given altitude is decreased by increasing the ram-recovery ratio. As an example, if the ram-recovery ratio of the air-induction system is increased from 0.70 to 0.90, the typical fighter airplane would reach an altitude of 40,000 feet in 11.4 minutes instead of in 13 minutes. In addition, the fuel consumed in climbing to 40,000 feet would be reduced from 525 pounds to 490 pounds.

Range.- The effect of ram-recovery ratio on the maximum range of the airplane, for altitudes of 20,000 and 40,000 feet, is shown in figure 17. It was assumed that the flight for maximum range was made at constant altitude. The engine speed and airplane velocity decreased as the fuel load was consumed. However, the magnitude of these changes was small. A description of the method used for calculating range is given in reference 4. The flight condition for maximum range was considered to be at the point of tangency of the drag versus velocity curve and of the thrust versus velocity curve representing a constant fuel consumption per mile.

The range of the fighter airplane is seen, in figure 17, to vary considerably with ram-recovery ratio. It is also shown that the adverse effect of air-induction-system pressure losses on range increases with altitude.

At lower ram-recovery ratios, the jet engine of the airplane must operate at a higher percentage of its rated rotational speed

for best range flight. Thus the fuel consumption per mile is increased and the range is reduced. The following table gives the percent of rated rotational speed of the jet engine and the cruising velocity, at a point during flight for maximum range where the fuel has been consumed.

Ram-recovery ratio $\frac{H_1 - p_o}{H_o - p_o}$	20,000 feet		40,000 feet	
	V_o	Percent N	V_o	Percent N
0.20	361	85.0	399	89.7
.60	368	83.7	402	86.9
1.00	370	82.3	410	84.7

CONCLUSIONS

In an analysis of the effect of pressure recovery on the performance of a jet-propelled airplane, it is shown that:

1. Ram-recovery ratio $\frac{H_1 - p_o}{H_o - p_o}$ was the parameter most suitable to indicate the efficiency of the air-induction system.

2. Reduction in ram-recovery ratio considerably reduced the net thrust and increased the specific fuel consumption of the typical jet engine.

3. The resultant effects on the performance of a fighter-type airplane powered by this typical jet engine were of sufficient magnitude to make high efficiency of the air-induction system of major importance.

4. As airplanes are developed which have higher drag-divergence Mach numbers and which utilize more powerful jet engines, high ram-recovery ratios for the air-induction systems will become even more necessary, if maximum performance is to be realized.

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APPENDIX A

Relation between Ram-Recovery Ratio and Mach Number

By definition, the ram-recovery ratio is

$$\frac{H_1 - p_o}{H_o - p_o} \text{ or } \frac{\frac{H_1}{p_o} - 1}{\frac{H_o}{p_o} - 1} \tag{A1}$$

For an isentropic process

$$p_o = H_o \left(1 + \frac{\gamma - 1}{2} M_o^2\right)^{-\frac{\gamma}{\gamma-1}} \tag{A2}$$

Substituting $\left(1 + \frac{\gamma - 1}{2} M_o^2\right)^{\frac{\gamma}{\gamma-1}}$ for $\frac{H_o}{p_o}$ in the equation for the ram-recovery ratio, the following expression is obtained:

$$\frac{H_1 - p_o}{H_o - p_o} = \frac{\frac{H_1}{H_o}\left(1 + \frac{\gamma - 1}{2} M_o^2\right)^{\frac{\gamma}{\gamma-1}} - 1}{\left(1 + \frac{\gamma - 1}{2} M_o^2\right)^{\frac{\gamma}{\gamma-1}} - 1} \tag{A3}$$

or

$$\frac{H_1}{H_o} = \frac{\frac{H_1 - p_o}{H_o - p_o}\left[\left(1 + \frac{\gamma - 1}{2} M_o^2\right)^{\frac{\gamma}{\gamma-1}} - 1\right] + 1}{\left(1 + \frac{\gamma - 1}{2} M_o^2\right)^{\frac{\gamma}{\gamma-1}}}$$

The ram-recovery ratio may also be written as

$$1 - \frac{H_o - H_1}{q_o\,(1 + \eta)}$$

where the term $(1 + \eta)$ is the compressibility correction. It should be noted that at low Mach numbers the ram-recovery ratio may be approximated by $1 - \left(\frac{\Delta H}{q_o}\right)$, since the compressibility correction is small.

APPENDIX B

Derivation of the Energy Ratio

Using the energy equation

$$c_p\, t_o + \frac{V_o^2}{2g} = c_p\, T_o \tag{B1}$$

and the relation

$$\frac{t_o}{T_o} = \left(\frac{p_o}{H_o}\right)^{\frac{\gamma-1}{\gamma}} \tag{B2}$$

the following equation is obtained:

$$\frac{V_o^2}{2g} = c_p\left[T_o - T_o\left(\frac{p_o}{H_o}\right)^{\frac{\gamma-1}{\gamma}}\right] \tag{B3}$$

This quantity represents the actual kinetic energy per pound of the free-stream air. At the compressor inlet the pressure is H_1 and the air temperature is T_1. V_1 is assumed to be equal to zero. If these quantities are reconverted to free-stream conditions where the free-stream static pressure is p_o, an air velocity of V_o' is obtained which is less than V_o because of pressure losses in the duct system. Equation (B3) then becomes

$$\frac{(V_o')^2}{2g} = c_p\left[T_1 - T_1\left(\frac{p_o}{H_1}\right)^{\frac{\gamma-1}{\gamma}}\right] \tag{B4}$$

Since the air flow through the duct system is assumed to be adiabatic, $T_1 = T_o$ and the ratio of the kinetic energy recovered to the kinetic energy available is

$$\frac{\left[T_o - T_o\left(\frac{p_o}{H_1}\right)^{\frac{\gamma-1}{\gamma}}\right]}{\left[T_o - T_o\left(\frac{p_o}{H_o}\right)^{\frac{\gamma-1}{\gamma}}\right]} \tag{B5}$$

Since

$$p_o = H_o\left(1 + \frac{\gamma - 1}{2} M_o^2\right)^{-\frac{\gamma}{\gamma-1}}$$

the ratio of the kinetic energy recovered to the kinetic energy available may be expressed, in terms of M_0 and H_0/H_1, as

$$1 - \frac{2}{(\gamma - 1) M_0^2} \left[\left(\frac{H_0}{H_1}\right)^{\frac{\gamma-1}{\gamma}} - 1\right] \tag{B6}$$

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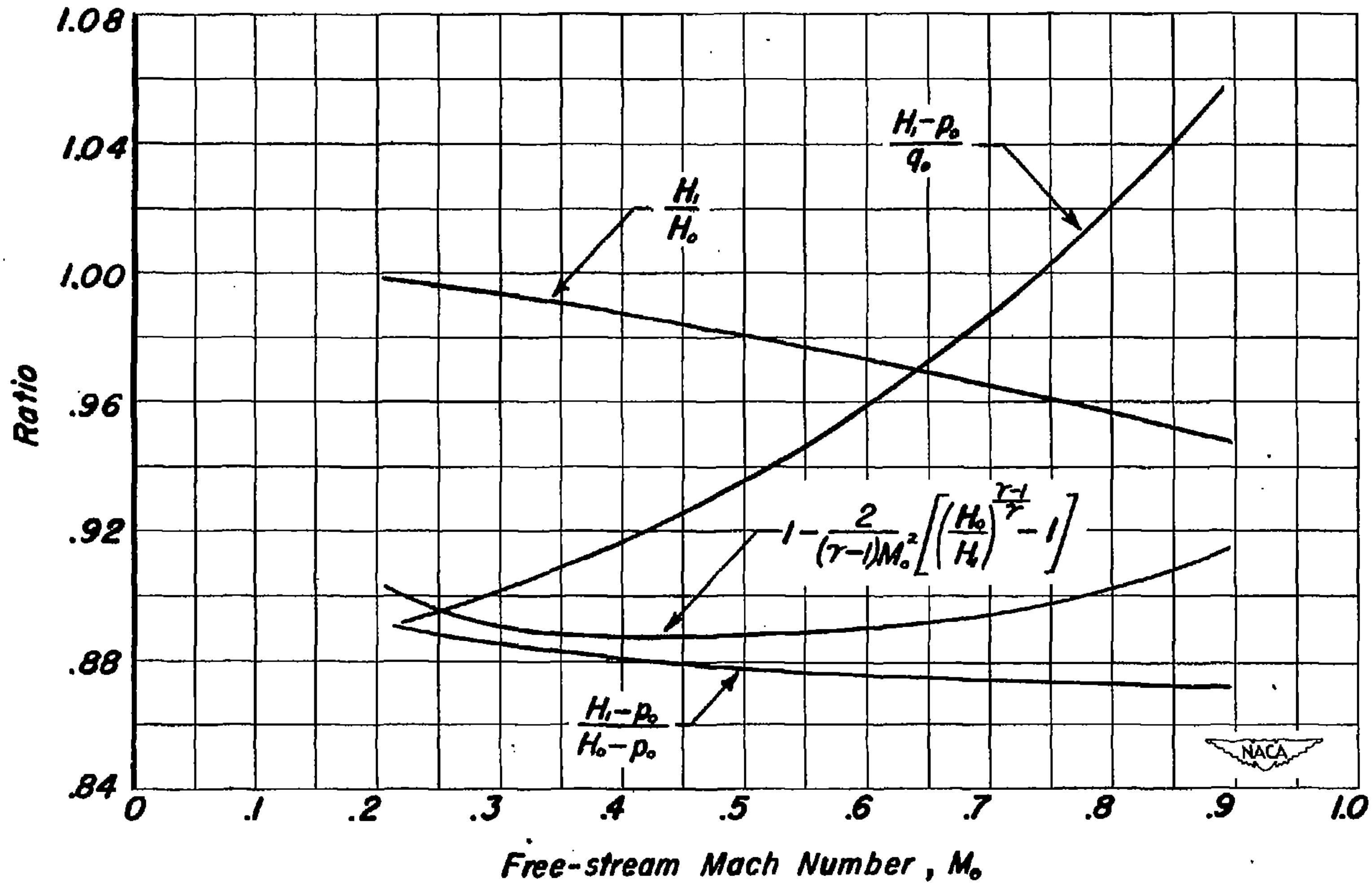


Figure 1.– Variation with Mach number of parameters used to indicate air-induction system efficiency. Based upon experimental data from reference 1.

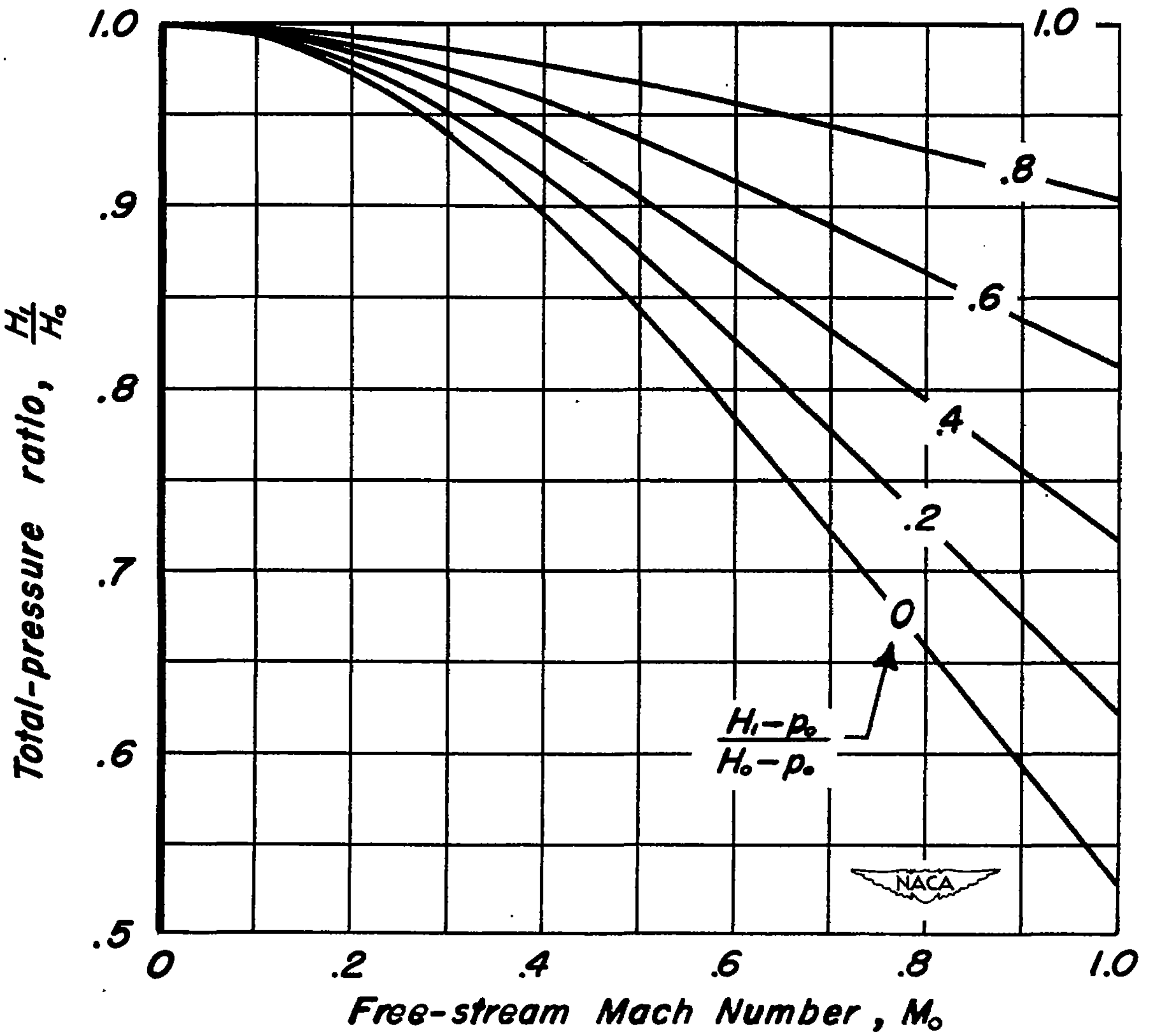


Figure 2.– Computed variation of total-pressure ratio with free-stream Mach number for constant values of ram-recovery ratio.

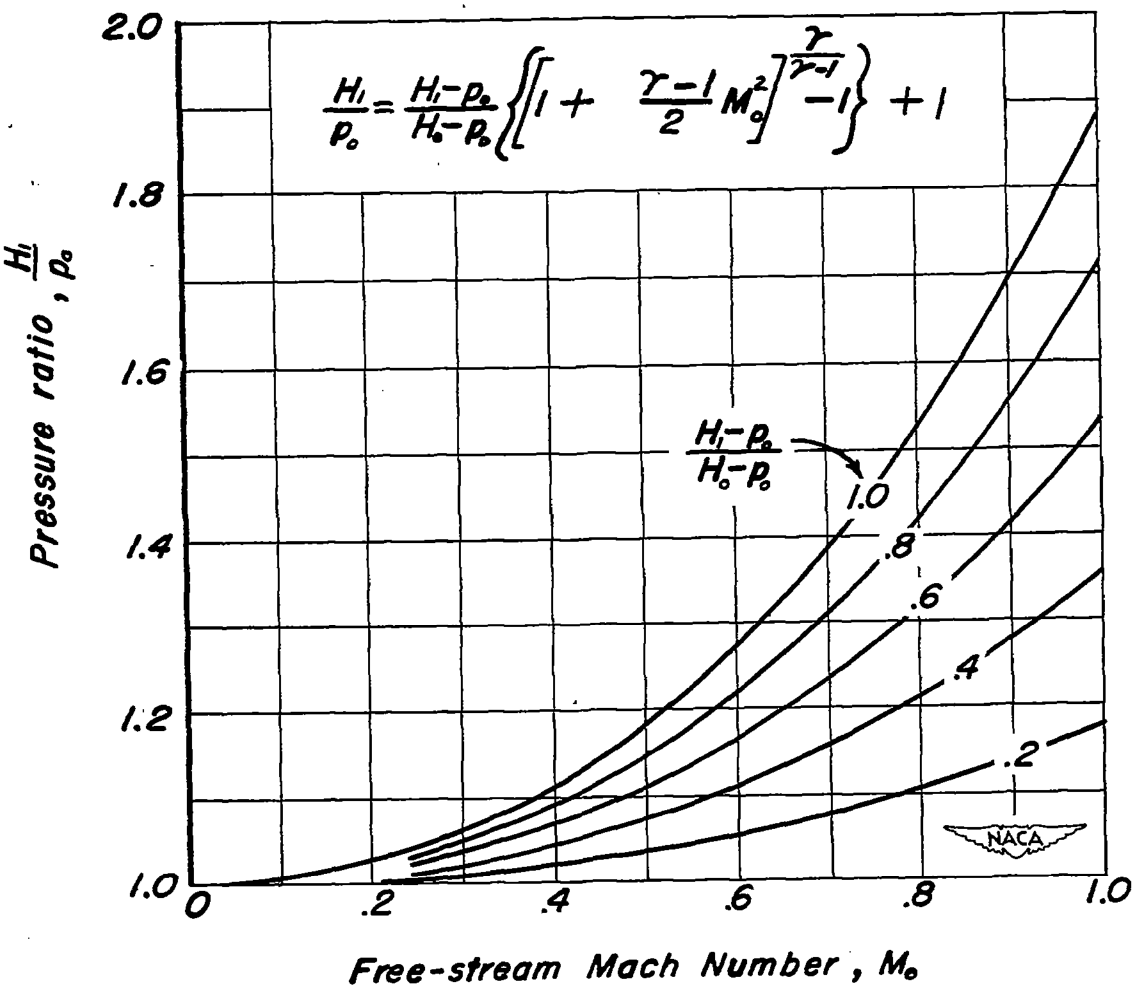


Figure 3.– Computed variation of pressure ratio with free-stream Mach number for constant values of ram-recovery ratio.

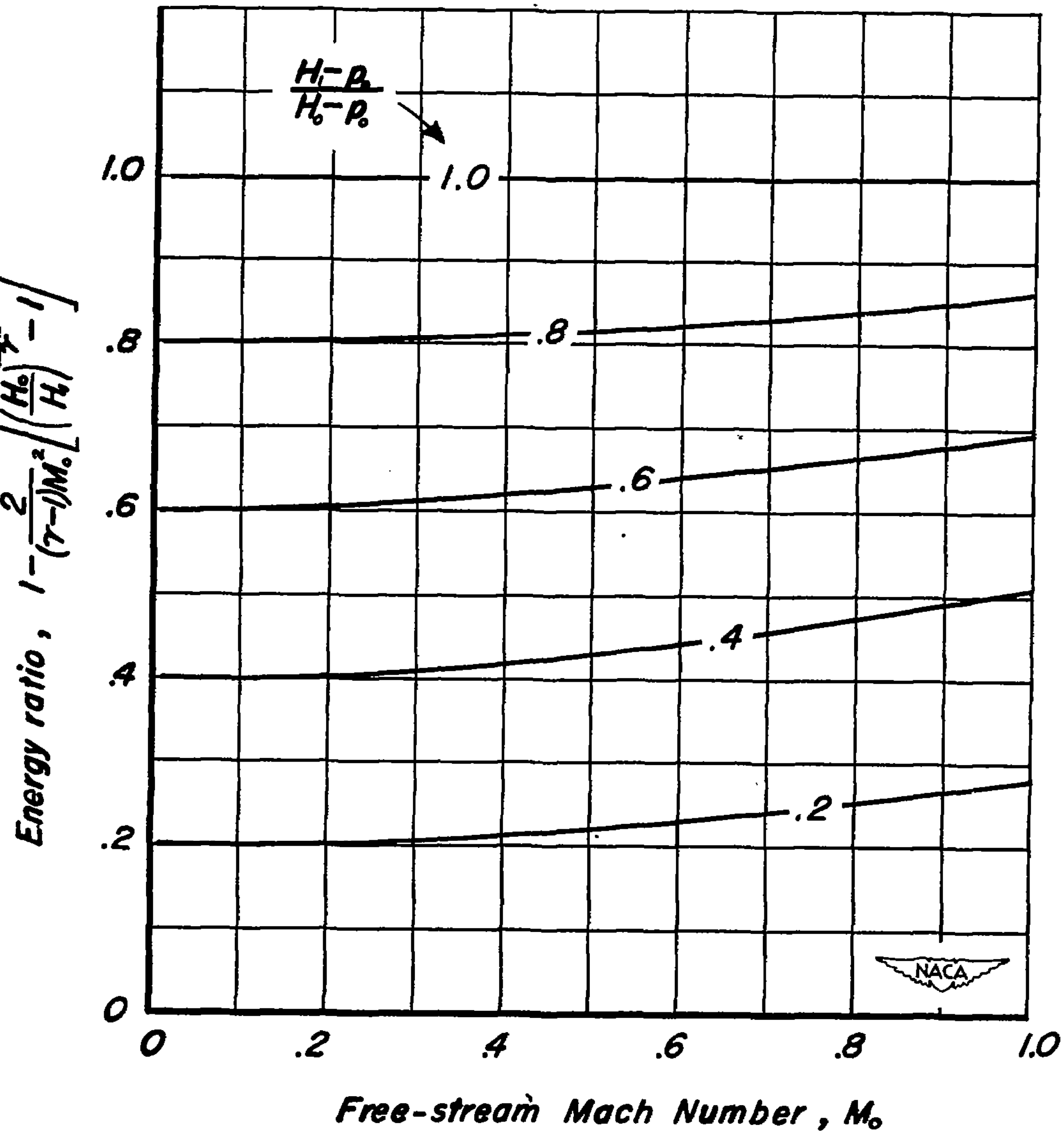
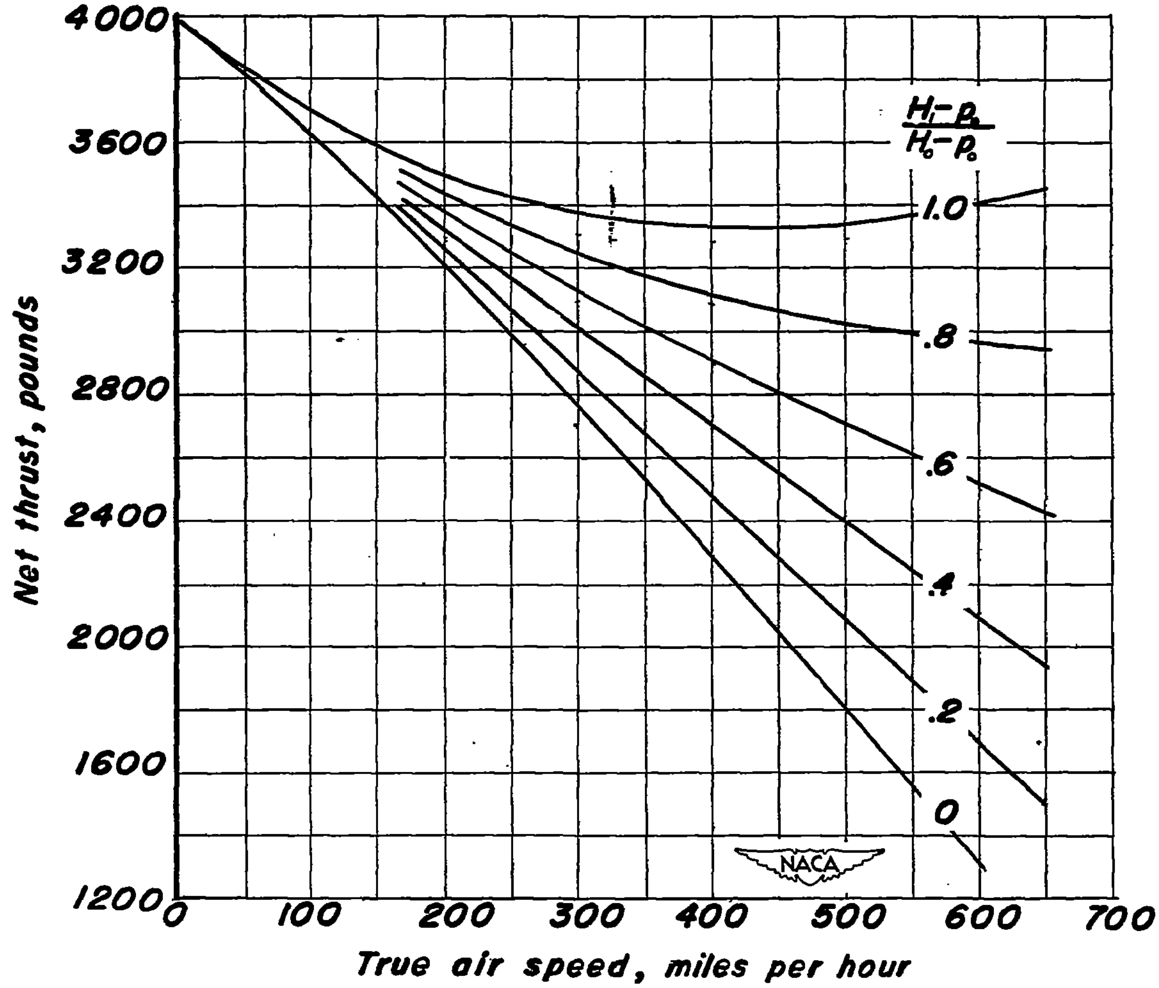
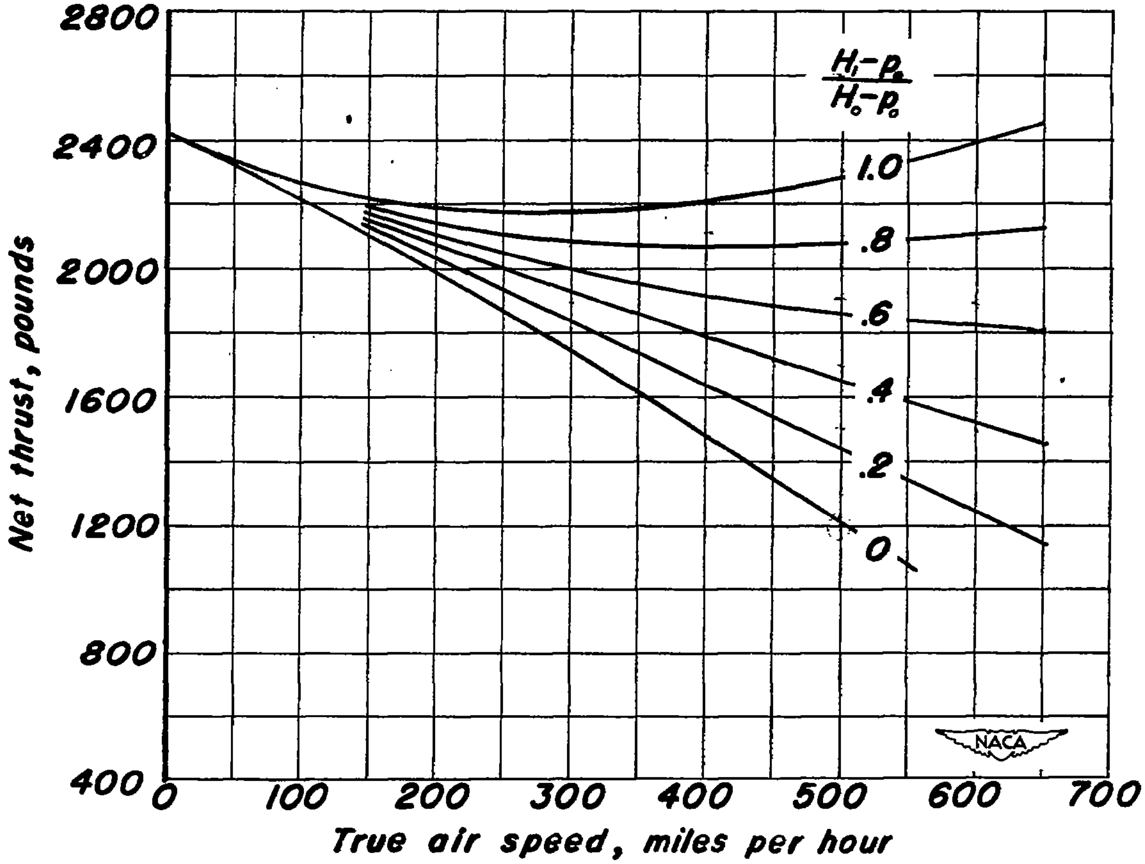


Figure 4.— Computed variation of energy ratio with free-stream Mach number for constant values of ram-recovery ratio.

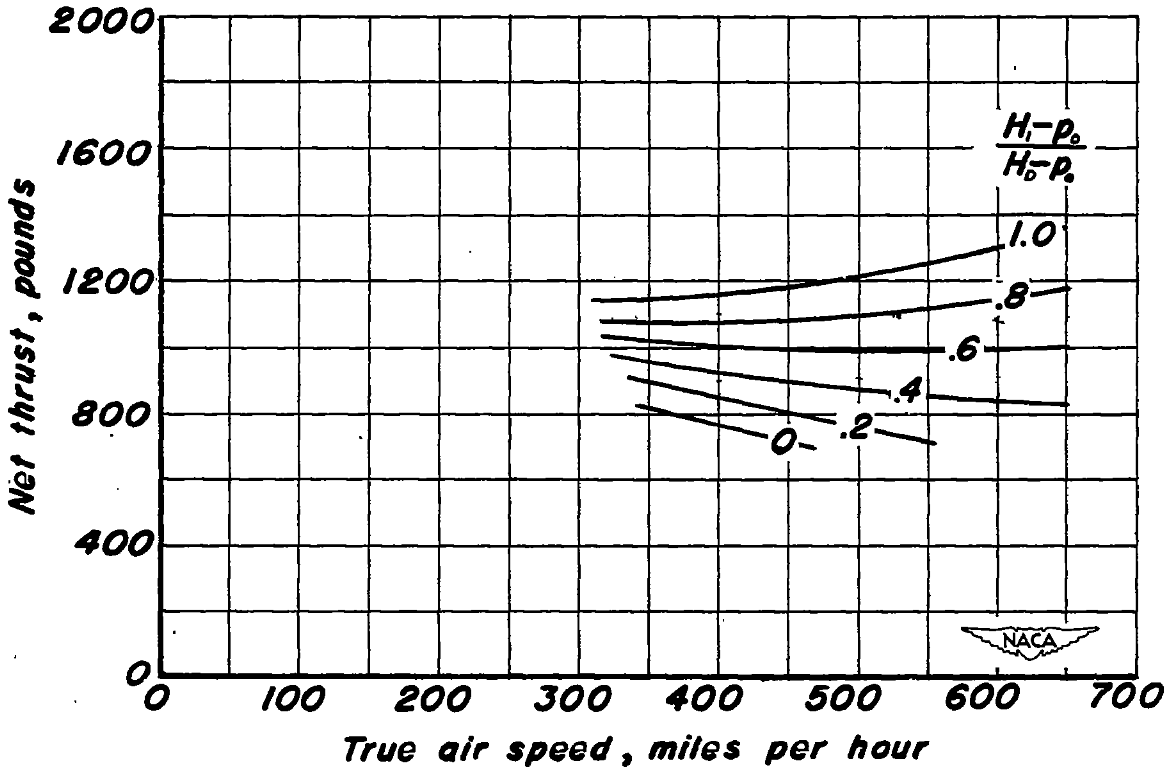


(a) Sea level.

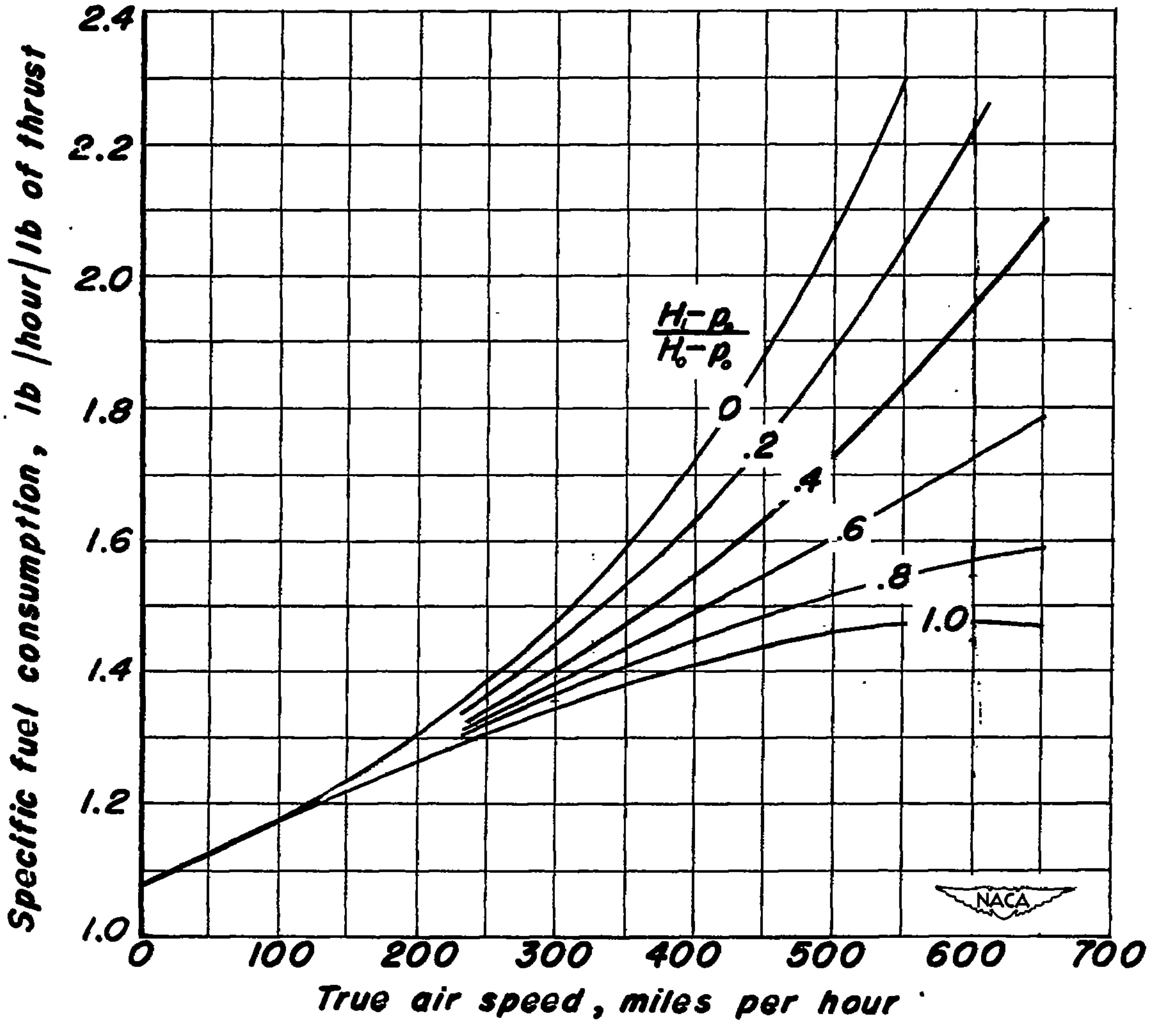
Figure 5.— Effect of ram-recovery ratio on the maximum available net thrust of a turbojet engine.



(b) 20,000 feet.
Figure 5.– Continued.

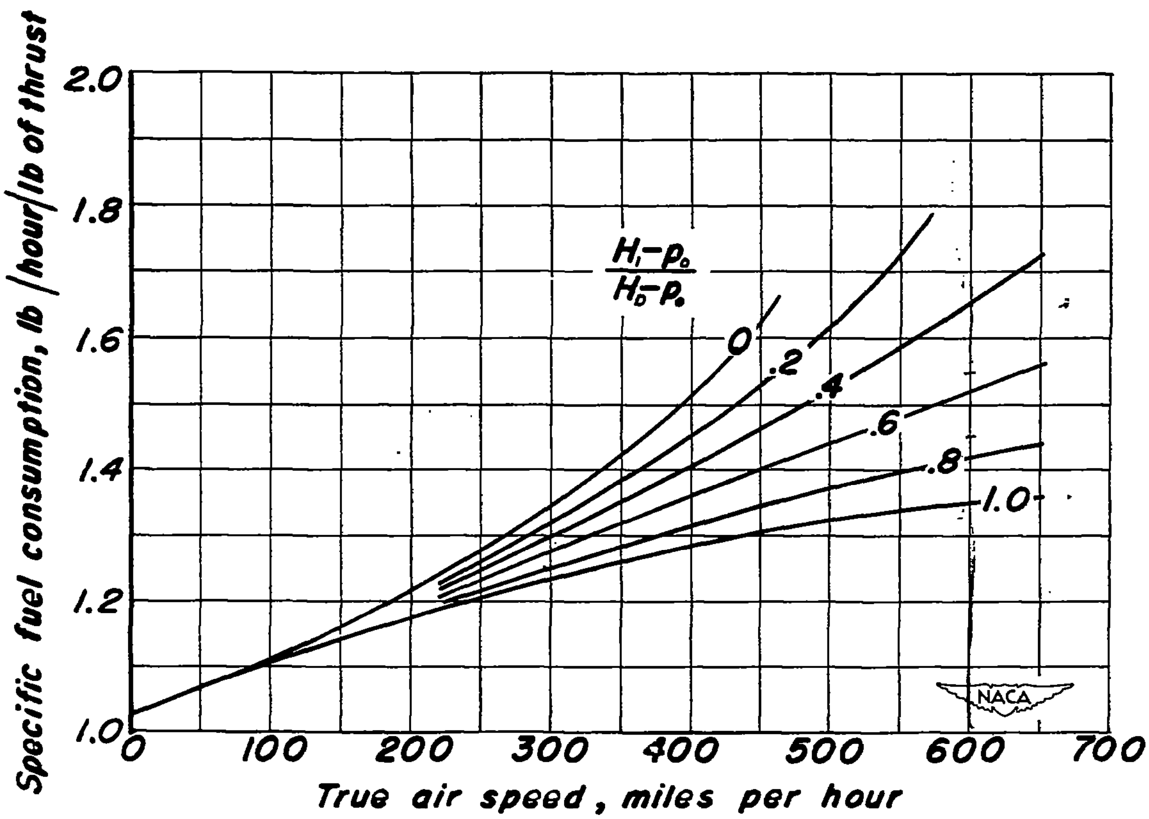


(c) 40,000 feet.
Figure 5.– Concluded.

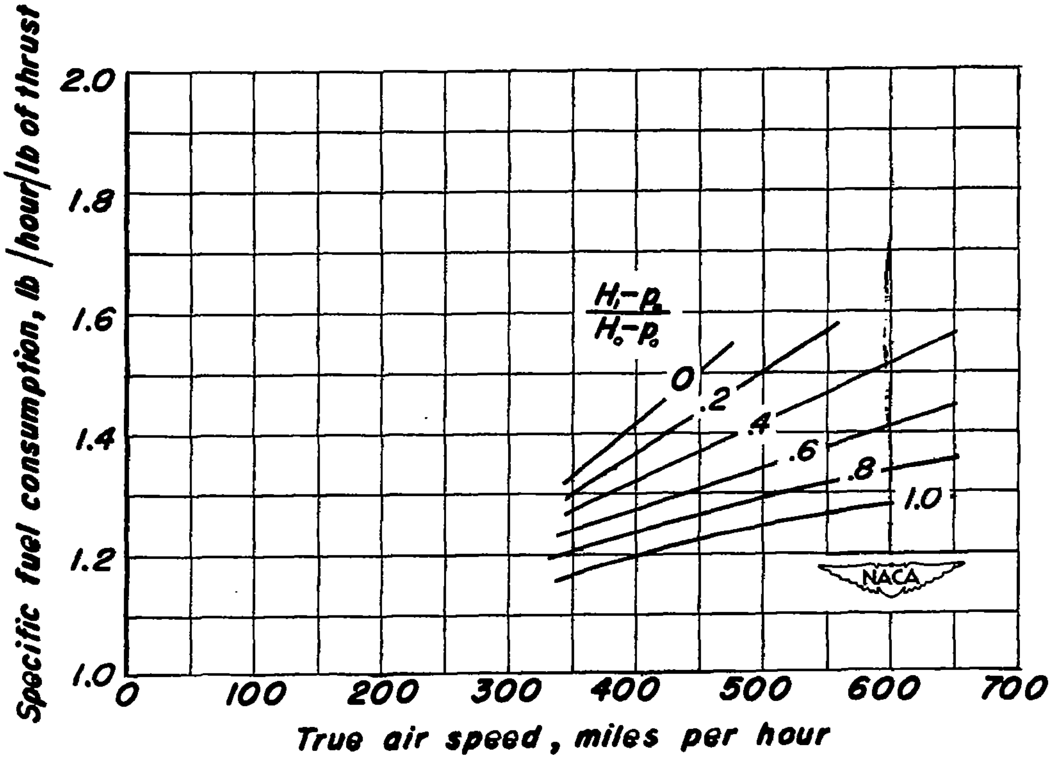


(a) Sea level.

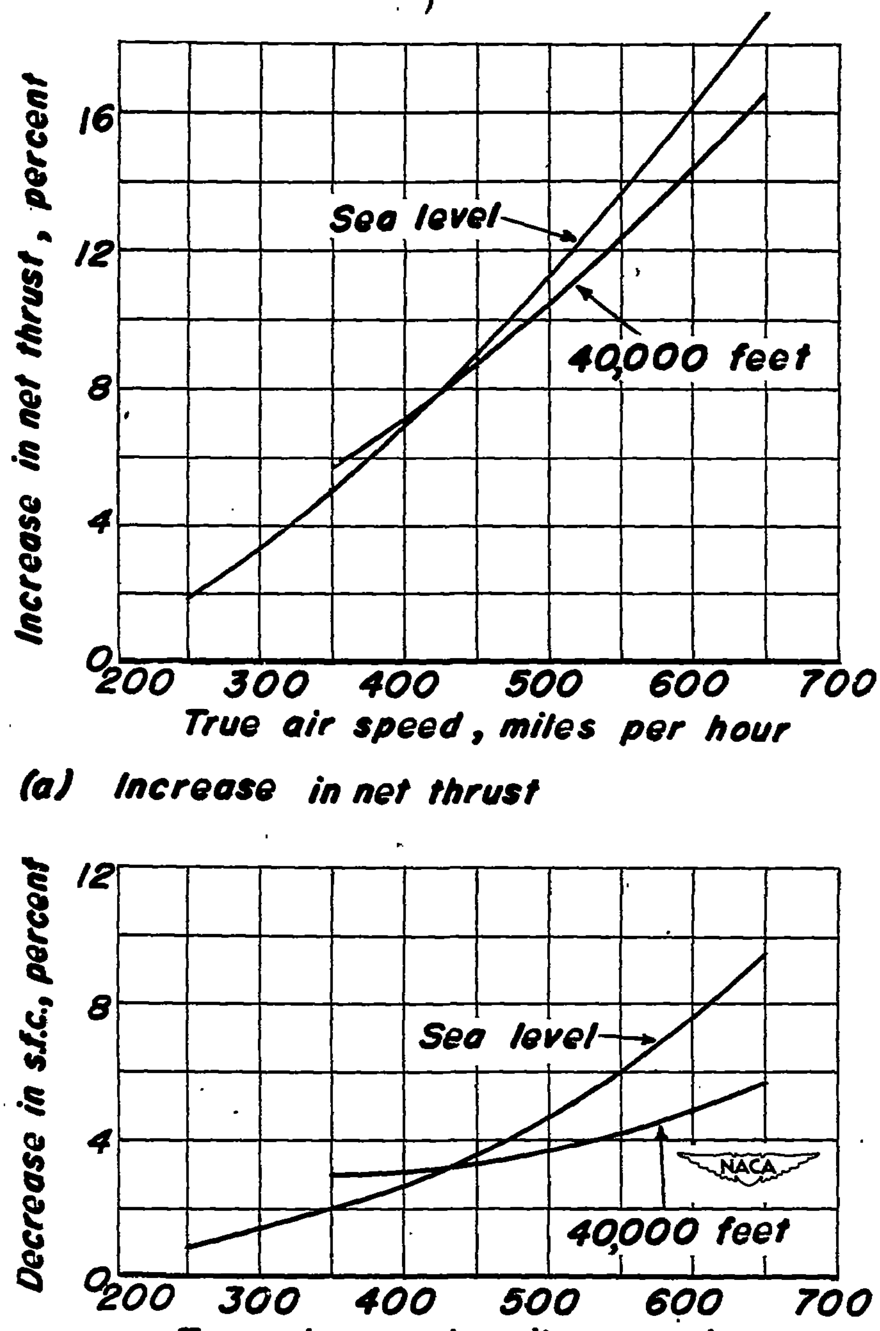
Figure 6.— Effect of ram-recovery ratio on the specific fuel consumption at maximum available net thrust of a typical turbojet engine.



(b) 20,000 feet.
Figure 6.– Continued.



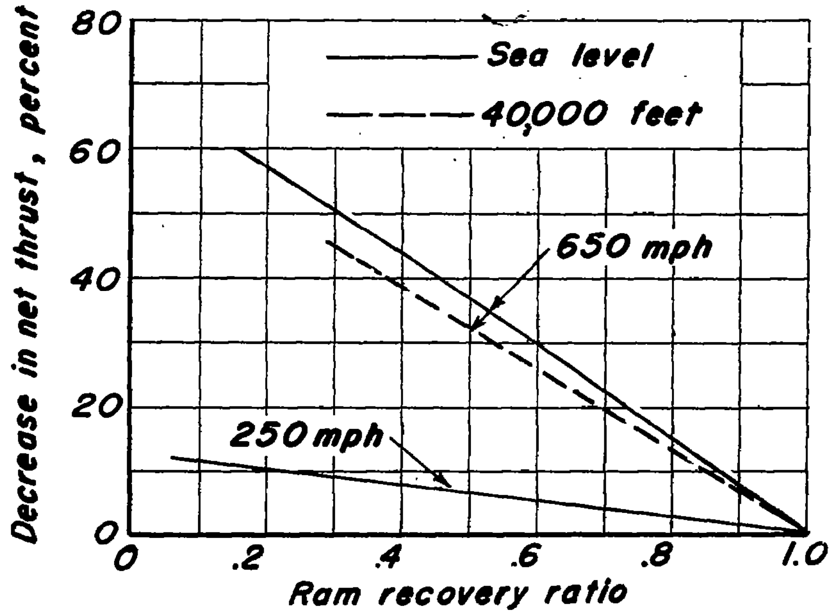
(c) 40,000 feet.
Figure 6.– Concluded.



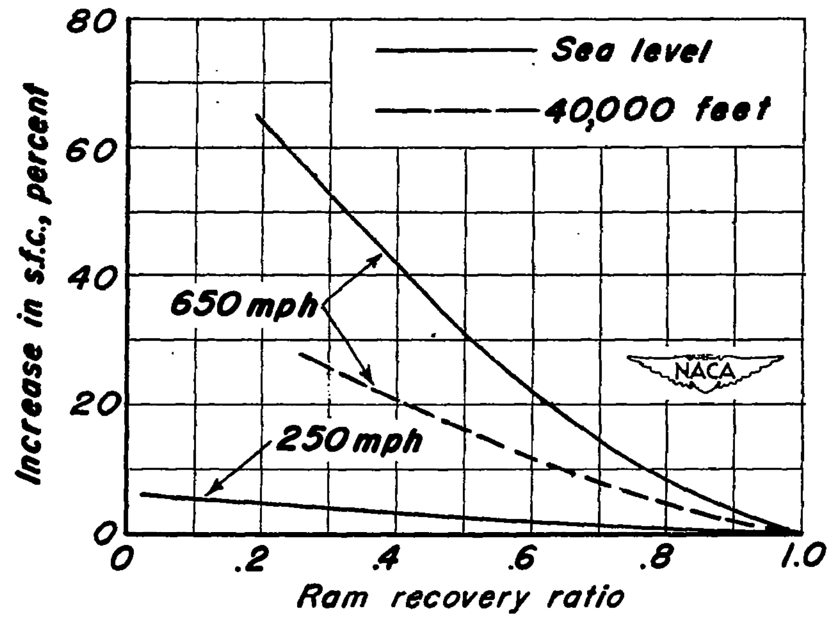
(a) Increase in net thrust

(b) Decrease in specific fuel consumption.

Figure 7.– Change in net thrust and specific fuel consumption for an increase in ram-recovery ratio from 0.70 to 0.90.



(a) Decrease in net thrust



(b) Increase in specific fuel consumption.

Figure 8.– Variation of net thrust and specific fuel consumption with decreasing ram-recovery ratio.

Gross weight	*12000 lb*
Wing area	*240 sq ft*
Fuel load	*3120 lb*
Aspect ratio	*7*

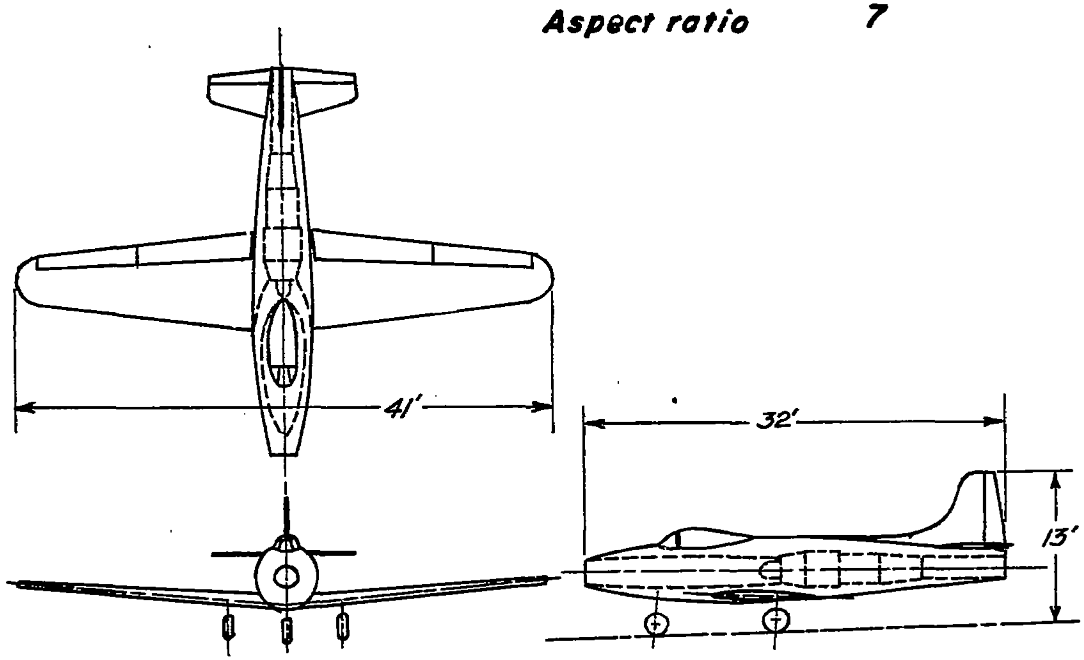


Figure 9.– Typical turbojet airplane.

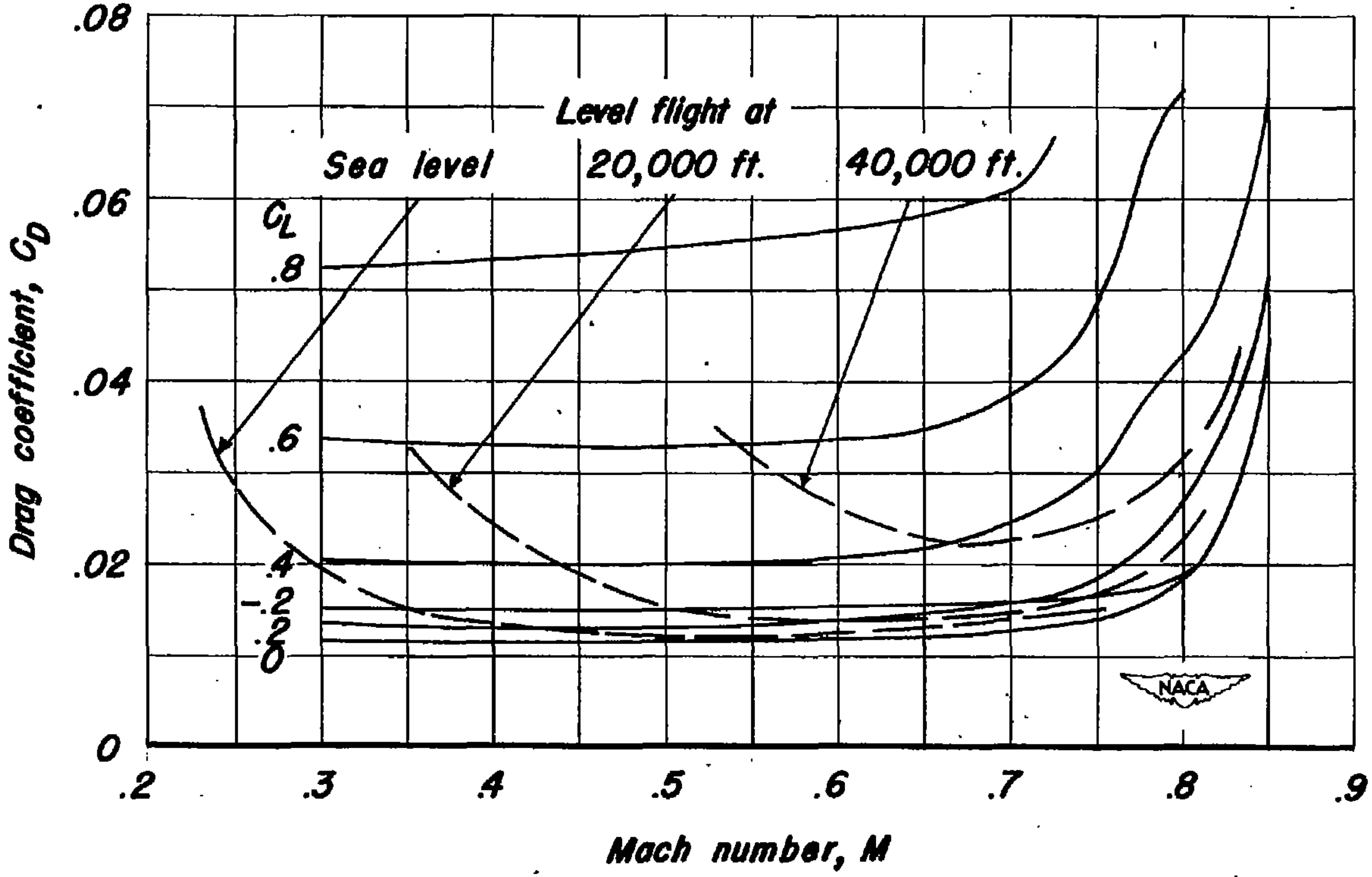


Figure 10.– Drag characteristics of the typical fighter airplane.

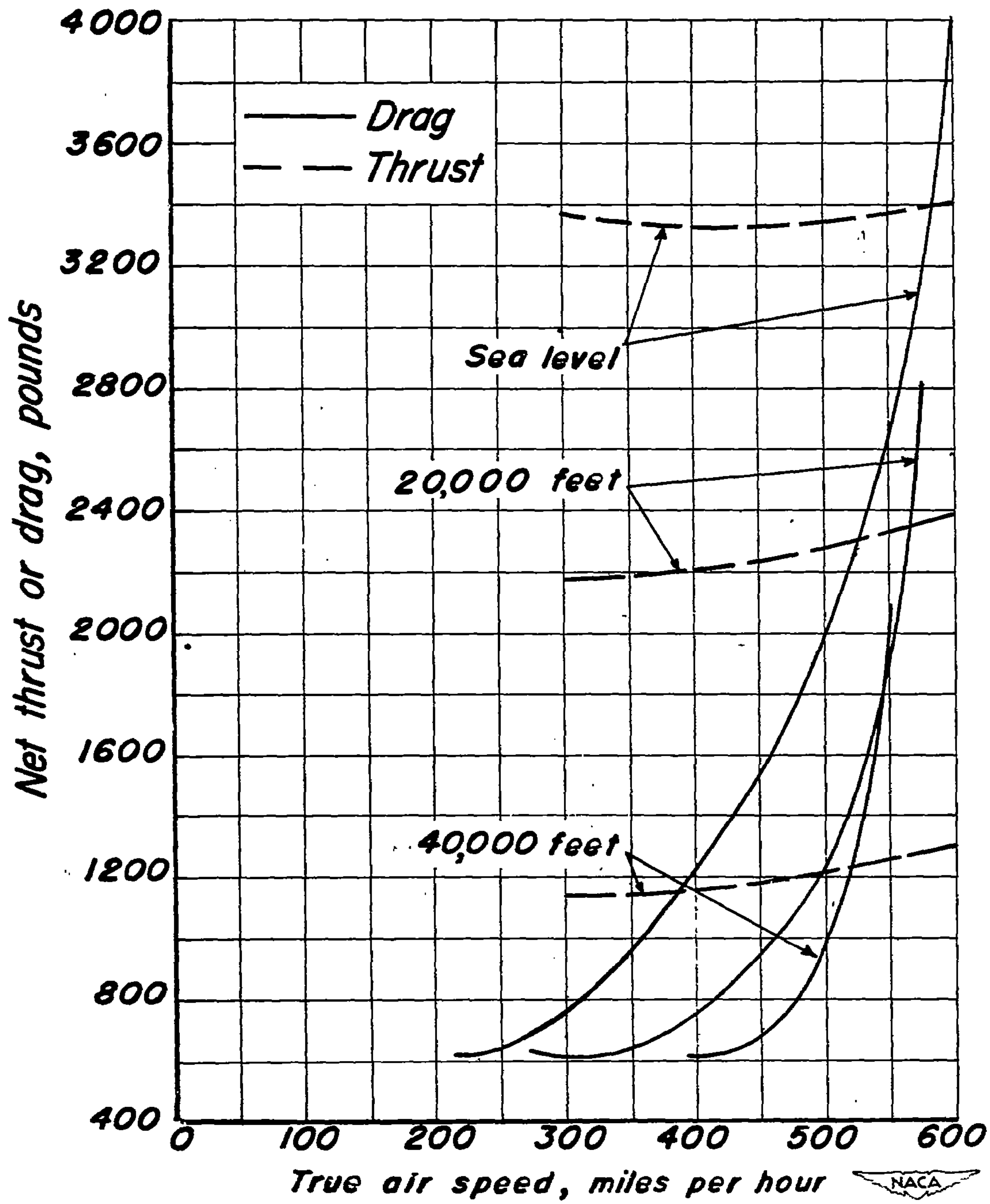


Figure 11.- Total drag for level flight and net thrust. N, 100 percent; Ram-recovery ratio, 1.00.

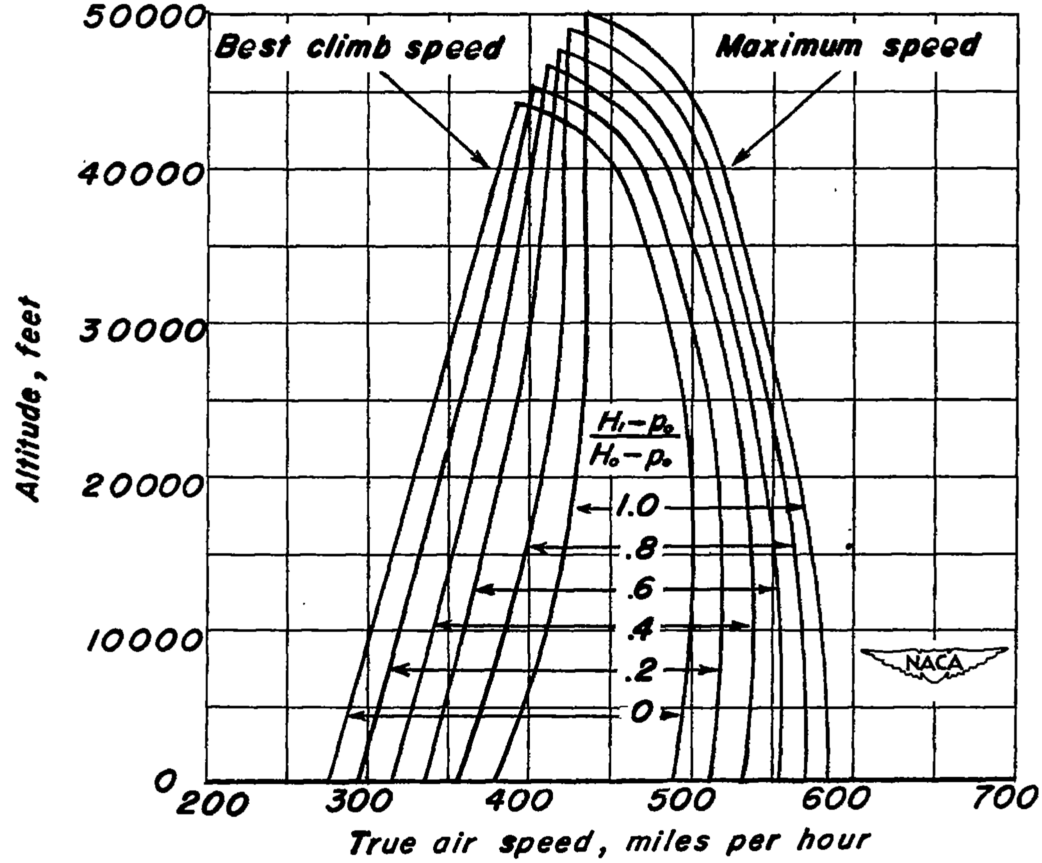


Figure 12.– Effect of ram-recovery ratio on the maximum level flight speed and best climb speed for a typical turbojet airplane.

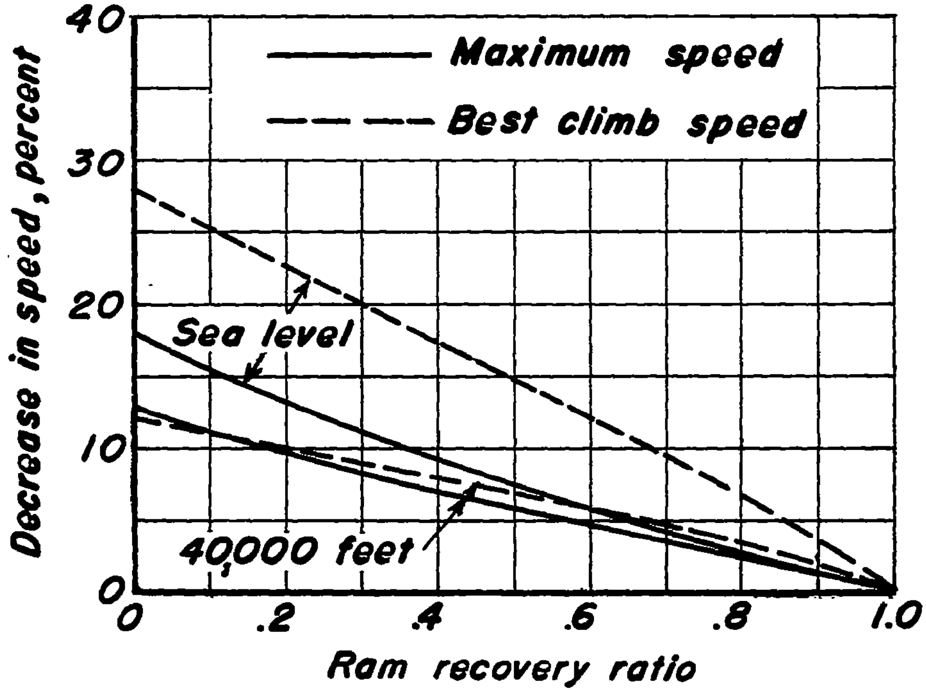


Figure 13.– Percent change in maximum level flight speed and best climb speed with decreasing ram-recovery ratio.

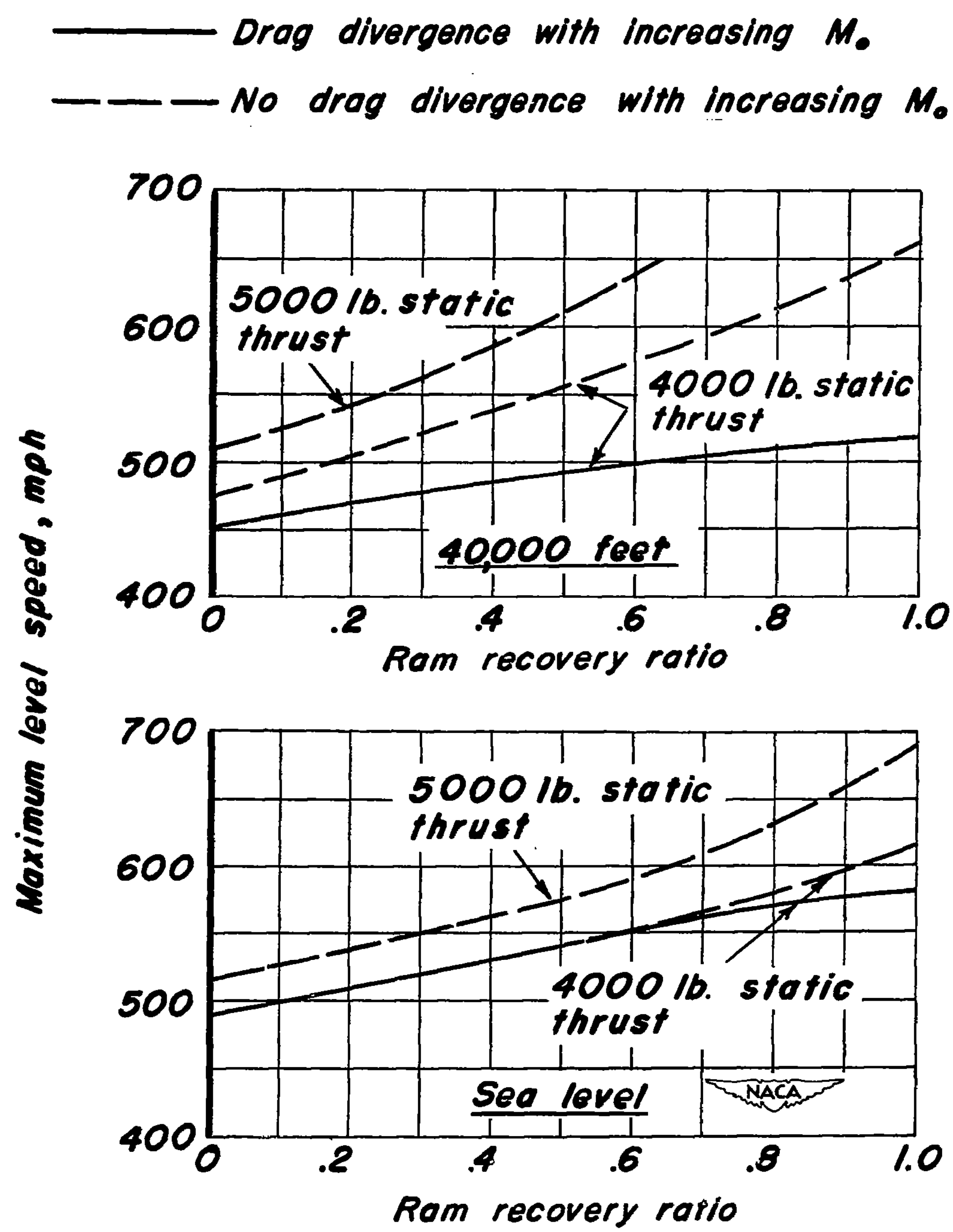


Figure 14.– Effect of ram-recovery ratio on the maximum level speed of a typical turbojet airplane.

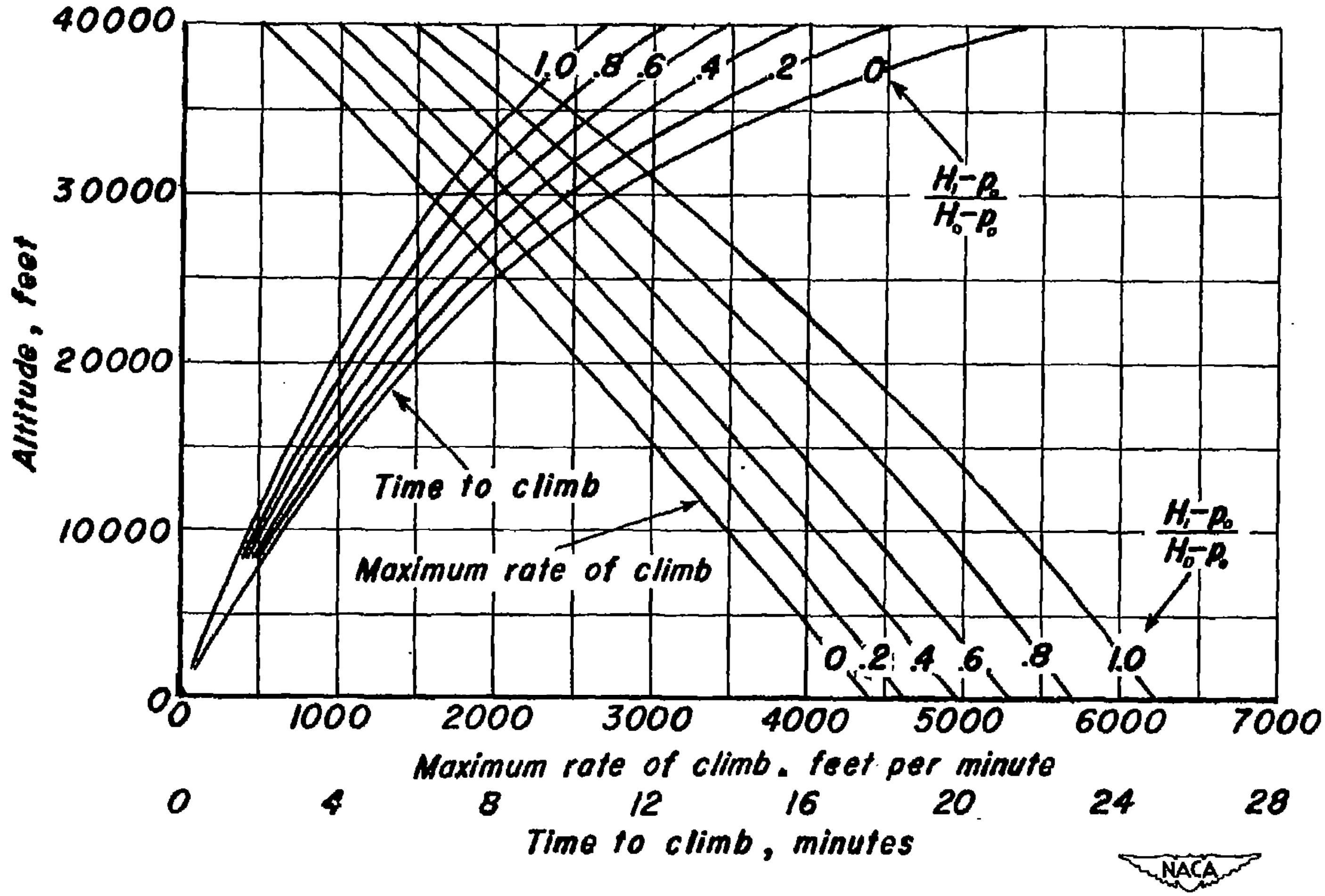


Figure 15.– Effect of ram-recovery ratio on the rate of climb and time to climb for a typical turbojet airplane.

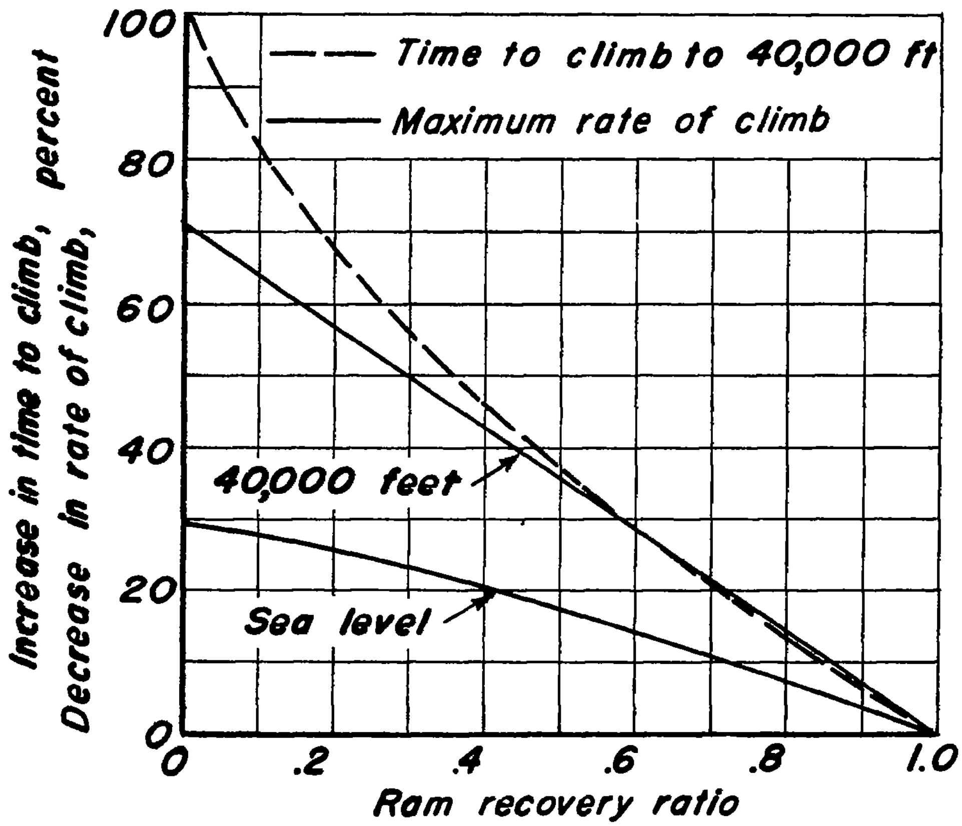


Figure 16.– Percent change in the rate of climb and time to climb to 40,000 feet with decreasing ram-recovery ratio for a typical turbojet airplane.

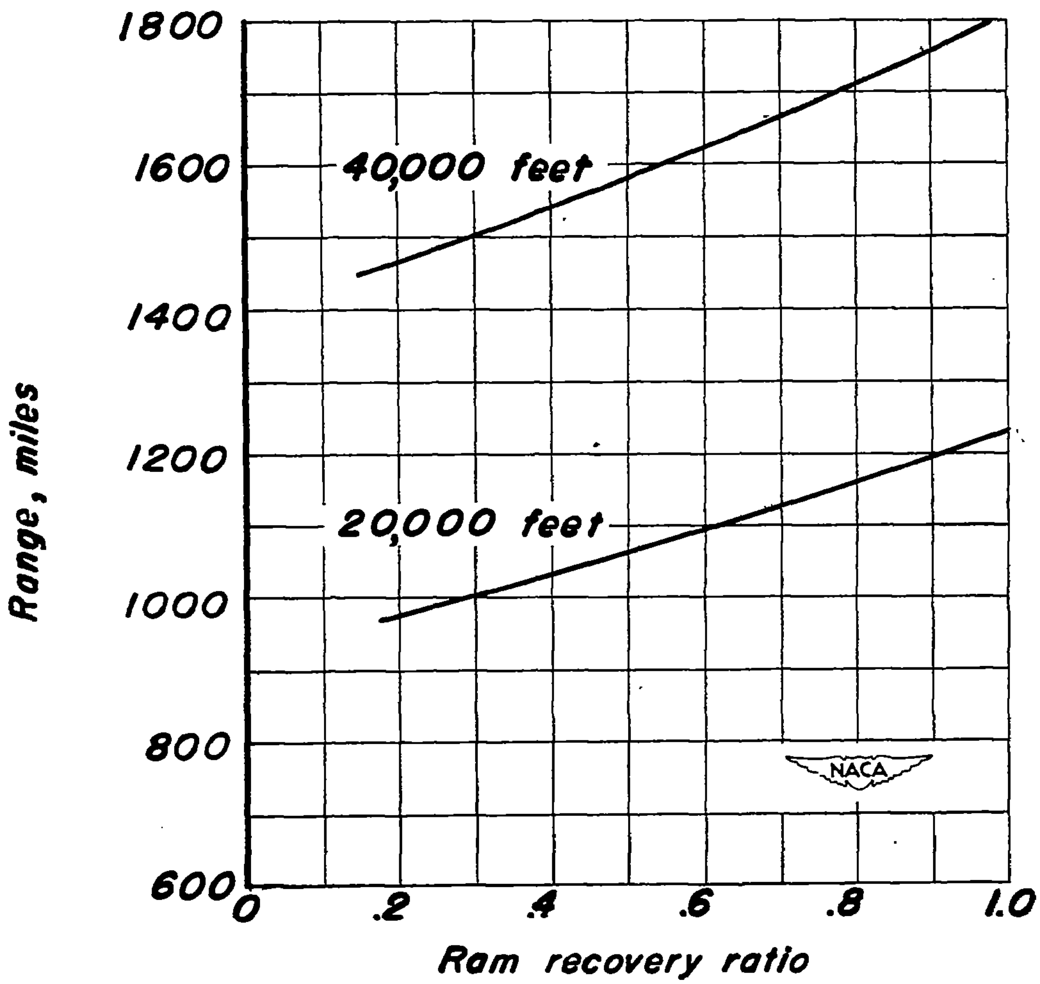


Figure 17.– Effect of ram-recovery ratio on the range of a typical turbojet airplane.